

sensible progress beyond his fellows who had continued doing their ordinary more varied work. Though some part of this might be owing to his being outside the regular classes, yet by far the greater part was due to the monotonous work palling upon him and dulling his brain.

The education of young children should be made like their picture-books. The pictures should be such as will induce the little learner to read and study the letterpress in order to find out more about them, and for that purpose they can scarcely be too numerous. A boy when his mind first opens to the world around him is like a man in a large strange house. He must needs go about and learn the arrangement of the building, peer into every room, examine the varied prospect from every window, before he can decide which rooms he will make his own; but when once he has made his choice, he will probably keep to one or two rooms and seldom enter the others.*

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THE THEORY OF "STREAM LINES" IN RELATION TO THE RESISTANCE OF SHIPS†

THE address of the President of a Section would year by year possess an appropriate interest, if it could always consist of an exposition of the progress made during the past year in the department of science which the Section embraces. And many of the addresses to this and other sections have conformed to this pattern with marked success.

But the adequate preparation of an address shaped in this approved mould would require a range of experience and a grasp of thought such as few possess; and custom has wisely sanctioned a type of address which, though less appropriate to the occasion, need not be either uninteresting or inapposite. And we, in this Section, have not to search far for instances in which its President has charmed and instructed us by a masterful exposition of some single subject in practical science, or by a timely reminder of the improvident manner in which we deal with some precious store of natural wealth.

I must express a hope that it will not be regarded as a conversion of liberty into license, if the subject I have chosen obliges me to introduce a further innovation, and to use diagrams and experiments in order to make my meaning clear.

I propose to treat of certain of the fundamental principles which govern the behaviour of fluid, and this with special reference to the resistance of ships. By the term "resistance" I mean the opposing force which a ship experiences in its progress through the water.

Considering the immense aggregate amount of power expended in the propulsion of ships, or, in other words, in overcoming the resistance of ships, I trust you will look favourably on an attempt to elucidate the causes of this resistance. It is true that improved results in ship-building have been obtained through accumulated experience; but it unfortunately happens that many of the theories by which this experience is commonly interpreted, are interwoven with fundamental fallacies, which, passing for principles, lead to mischievous results when again applied beyond the limits of actual experience.

The resistance experienced by ships is but a branch of the general question of the forces which act on a body moving through a fluid, and has within a comparatively recent period been placed in an entirely new light by what is commonly called the theory of stream-lines.

The theory as a whole involves mathematics of the highest order, reaching alike beyond my ken and my purpose; but I believe that, so far as it concerns the resistance of ships, it can be sufficiently understood without the help of technical mathematics; and I will endeavour to explain the course which I have myself found most conducive to its easy apprehension.

It is convenient to consider first the case of a completely submerged body moving in a straight line with uniform speed through an unlimited ocean of fluid. A fish in deep water, a submarine motive torpedo, a sounding lead while descending

through the water, if moving at uniform speed, are all examples of the case I am dealing with.

It is a common but erroneous belief that a body thus moving experiences resistance to its onward motion by an increase of pressure on its head end, and a diminution of pressure on its tail end. It is thus supposed that the entire head end of the body has to keep on exerting pressure to drive the fluid out of the way, to force a passage for the body, and that the entire tail end has to keep on exerting a kind of suction on the fluid to induce it to close in again—that there is, in fact, what is termed *plus* pressure throughout the head end of the body, and *minus* pressure or partial vacuum throughout the tail end.

This is not so; the resistance to the progress of the body is not due to these causes. The theory of stream-lines discloses to us the startling but true proposition, that a submerged body, if moving at a uniform speed through a perfect fluid, would encounter no resistance whatever. By a perfect fluid, I mean a fluid which is free from viscosity, or quasi-solidity, and in which no friction is caused by the sliding of the particles of the fluid past one another, or past the surface of the body.

The property which I describe as "quasi-solidity" must not be confused with that which persons have in their minds when they use the term "solid water." When people in this sense speak of water as being "solid," they refer to the *sensation* of solidity experienced on striking the water-surface with the hand, or to the reaction encountered by an oar-blade or propeller. What I mean by "quasi-solidity," is the sort of stiffness which is conspicuous in tar or liquid mud; and this property undoubtedly exists in water, though in a very small degree. But the sensation of solid reaction which is encountered by the hand or the oar-blade, is not in any way due to this property, but to the *inertia* of the water: it is in effect this inertia which is erroneously termed solidity; and this inertia is possessed by the perfect fluid, with which we are going to deal, as fully as by water. Nevertheless it is true, as I am presently going to show you, that the perfect fluid would offer no resistance to a submerged body moving through it at a steady speed. It will be seen that the apparent contradiction in terms which I have just advanced is cleared up by the circumstance, that in the one case we are dealing with steady motion, and in the other case with the initiation or growth of motion.

In the case of a completely submerged body in the midst of an ocean of perfect fluid, unlimited in every direction, I need hardly argue that it is immaterial whether we consider the body as moving uniformly through the ocean of fluid, or the ocean of fluid as moving uniformly past the body.

The proposition that the motion of a body through a perfect fluid is unresisted, or, what is the same thing, that the motion of a perfect fluid past a body has no tendency to push it in the direction in which the fluid is flowing, is a novel one to many persons; and to such it must seem extremely startling. It arises from a general principle of fluid motion, which I shall presently put before you in detail—namely, that to cause a perfect fluid to change its condition of flow in any manner whatever, and ultimately to return to its original condition of flow, does not require, nay, does not admit of, the expenditure of any power, whether the fluid be caused to flow in a curved path, as it must do in order to get round a stationary body which stands in its way, or to flow with altered speed, as it must do in order to get through the local contraction of channel which the presence of the stationary body practically creates. Power, it may indeed be said, is first expended, and force exerted to communicate certain motions to the fluid; but that same power will ultimately be given back, and the force counterbalanced, when the fluid yields up the motion which has been communicated to it, and returns to its original condition.

I shall commence by illustrating the action on a small scale by fluid flowing through variously shaped pipes; and I must premise that in the greater part of what I shall have to say, I shall not require to take account of absolute hydrostatic pressures. The flow of water through pipes is uninfluenced by the absolute pressure of the water.

I will begin with a very simple case, which I will treat in some detail, and which will serve to show the nature of the argument I am about to submit to you.

Suppose a rigid pipe of uniform sectional area, of the form shown in Fig. 1, something like the form of the water-line of a vessel.

The portions AB, BC, CD, DE are supposed to be equal in length, and of the same curvature, the pipe terminating at E in exactly the same straight line in which it commenced at A, so

* My experience has been entirely with boys, but I feel sure that elementary science might be taught with at least equal advantage to little girls.

† Address to the Mechanical Section of the British Association, Bristol, August 25, 1875; by William Froude, C.E., M.A., F.R.S. President of the Section. Revised and extended by the author.

that its figure is perfectly symmetric on either side of C, the middle point of its length.

Let us now assume that the pipe has a stream of perfect fluid

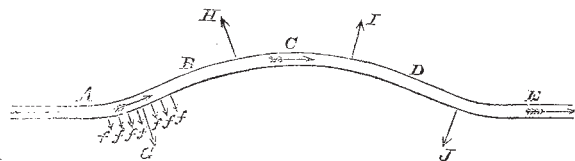


FIG. 1.

running through it from A towards E, and that the pipe is free to move bodily endways.

It is not unnatural to assume at first sight that the tendency of the fluid would be to push the pipe forward, in virtue of the opposing surfaces offered by the bends in it—that both the divergence between A and C from the original line at A, and the return between C and E to that line at E, would place parts of the interior surface of the pipe in some manner in opposition to the stream or flow, and that the flow thus obstructed would drive the pipe forward; but if we endeavour to build up these supposed causes in detail, we find the reasoning to be illusory.

I will now trace the results which can be established by correct reasoning.

The surface being assumed to be smooth, the fluid, being a perfect fluid, can exercise no drag by friction or otherwise on the side of the pipe in the direction of its length, and in fact can exercise no force on the side of the pipe, except at right angles to it. Now the fluid flowing round the curve from A to B will, no doubt, have to be deflected from its course, and, by what is commonly known as centrifugal action, will press against the outer side of the curve, and this with a determinable force. The magnitude and direction of this force at each portion of the curve of the pipe between A and B are represented by the small arrows marked *f*; and the aggregate of these forces between A and B is represented by the larger arrow marked *G*. In the same way the forces acting on the parts BC, CD, and DE are indicated by the arrows *H*, *I*, and *J*; and as the conditions under which the fluid passes along each of the successive parts of the pipe are precisely alike, it follows that the four forces are exactly equal, and, as shown by the arrows in the diagram, they exactly neutralise one another in virtue of their respective directions; and therefore the whole pipe from A to E, considered as a rigid single structure, is subject to no disturbing force by reason of the fluid running through it.

Though this conclusion that the pipe is not pushed endways may appear on reflection so obvious as to have scarcely needed elaborate proof, I hope that it has not seemed needless, even though tedious, to follow somewhat in detail the forces that act, and which are, under the assumed conditions, the *only* forces that act, on a symmetrical pipe such as I have supposed.

Having shown that in the case of this special symmetrically curved pipe the flow of a perfect fluid through it does not tend to push it endways, I will now proceed to show that this is also the case whatever may be the outline of the pipe, provided that its beginning and end are in the same straight line.

Assume a pipe bent, and its ends joined so as to form a complete circular ring, and the fluid within it running with velocity round the circle. This fluid, by centrifugal force, exercises a uniform outward pressure on every part of the uniform curve; and this is the only force the fluid can exert. This pressure tends to tear the ring asunder, and causes a uniform longitudinal tension on each part of the ring, in the same manner as the pressure within a cylindrical boiler makes a uniform tension on the shell of the boiler.

Now, in the case of fluid running round within rings of various diameter, just as in the case of railway trains running round curves of various diameter, if the velocity along the curve remain the same, the outward pressure on each part of the circumference is less, in proportion as the diameter becomes greater; but the circumferential tension of the pipe is in direct proportion to the pressure and to the diameter; and since the pressure has been shown to be inversely as the diameter, the tension for a given velocity will be the same, whatever be the diameter.

Thus, if we take a ring of doubled diameter, if the velocity is unchanged, the outward pressure per lineal inch will be halved; but this halved pressure, acting with the doubled diameter, will give the same circumferential tension.

Now this longitudinal tension is the same at every part of the

ring; and if we cut out a piece of the ring, and supply the longitudinal tension at the ends of the piece, by attaching two straight pipes to it tangentially (see Fig. 2), and if we maintain the flow of the fluid through it, the curved portion of the pipe will be under just the same strains as when it formed part of the com-

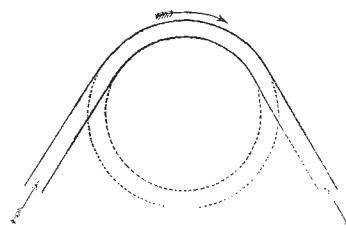


FIG. 2.

plete ring. It will be subject merely to a longitudinal tension; and if the pipe thus formed be flexible, and fastened at the ends, the flow of fluid through it will not tend to disturb it in any way. Whatever be the diameter of the ring out of which the piece is assumed to be cut, and whatever be the length of the segment cut out of it, we have seen that the longitudinal tension will be the same if the fluid be moving at the same velocity; so that, if we piece together any number of such bends of any lengths and any curvatures to form a pipe of any shape, such pipe, if flexible and fastened at the ends (see Fig. 3), will not be disturbed by the

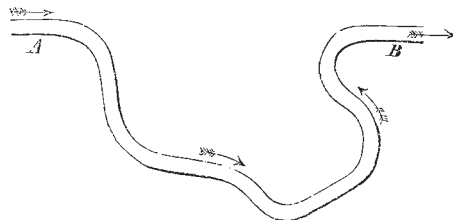


FIG. 3.

flow of fluid through it; and the equilibrium of each portion and of the whole of the combined pipe will be satisfied by a uniform tension along it.

Further, if the two ends of the pipe are in the same straight line, pointing away from one another (see Fig. 4), since the

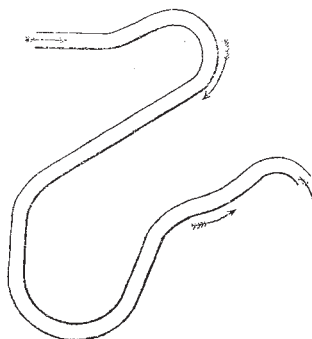


FIG. 4.

tensions on the ends of the pipe are equal and opposite, the flow of the fluid through it does not tend to push it bodily endways.*

This is the point which it was my object to prove; but in the course of this proof there has incidentally appeared the further proposition, that a flexible tortuous pipe, if fastened at the ends, will not tend to be disturbed in any way by the flow of fluid through it. This proposition may to some persons seem at first sight to be so paradoxical as to cast some doubt on the validity of the reasoning which has been used; but the proposition is nevertheless true, as can be proved by a closely analogous experiment, as follows:—

Imagine the ends of the flexible tortuous pipe to be joined so as to form a closed figure (see Fig. 5), there will then be no need for the imaginary fastenings at the ends, since each end will

* See Supplementary Note A.

supply the fastening to the other. Then substitute for the fluid flowing round the circuit of the pipe, a flexible chain, running in the same path. In this case the centrifugal forces of the chain running in its curved path are similar to those of the fluid flow-

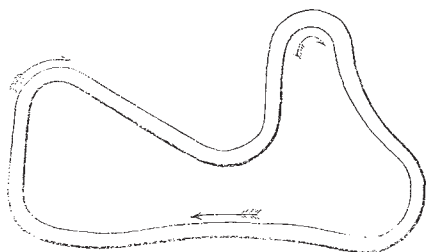


FIG. 5.

ing in the pipe; and the longitudinal tension of the chain represents in every particular the longitudinal tension on the pipe.

As a simple form of this experiment, if a chain be set rotating at a very high velocity over a pulley in the manner shown in Fig 6, it will be seen that the centrifugal forces do not tend to disturb the path of the running chain; and, indeed, the velocity being extremely great, the forces, in fact, tend to preserve the path of the chain in opposition to any disturbing cause. On the



FIG. 6.



FIG. 7.

other hand, if by sufficient force we disturb it from its path, it tends to retain the new figure which has been thus imposed upon it (see Fig. 7).

The apparatus with which I am about to verify this proposition has been lent to me by Sir W. Thomson. It is one which he has used on many occasions for the same purpose; and I must add that the proposition in his hands has formed the basis of conclusions incomparably deeper and more important than those to which I am now directing your attention.

You observe the chain when at rest hangs in the ordinary catenary form, from a large pulley with a very wide-mouthed groove and mounted in a frame which is secured to the ceiling. By a simple arrangement of multiplying bands the pulley is driven at a high speed, carrying the chain round by the frictional adhesion of its upper semi-circumference. When at its highest speed the chain travels about 40 per second.

The idea that the chain when thus put in motion will be disturbed by its centrifugal force from the shape it holds while at rest must point to one of two conclusions; either (1) the chain will tend to open out into a complete circle, or (2) it will on the contrary tend to stretch itself at its lower bend to a curvature of infinite sharpness.

But you observe that no tendency to either change of form appears. On the contrary, the chain, instead of taking spontaneously any new form in virtue of its centrifugal force, has plainly assumed a condition under which it is with difficulty disturbed, alike from its existing form, or from any other which I communicate to it by violently striking it. Such blows locally indent it almost as they would bend a bar of lead,

In spite, however, of this quasi-rigidity which its velocity has imparted to it, it does, if left to itself, slowly assume, as you perceive, a curious little contortion, both as it approaches and as it recedes from the lower bend of the catenary; and it is both interesting and instructive to trace the cause of the deformation.

I have already explained that the speed of the chain subjects it throughout to longitudinal tension. Speaking quantitatively, the tension is equal to the weight of a length of the chain twice the height due to the velocity. This is $\frac{v^2}{g}$, and thus, as the

speed is 40 feet per second, $\frac{1600}{32} = 50$ feet, or with this chain about 14 lbs.

Now in travelling through the lower bend of the catenary, the chain passes from being nearly straight, to being sharply curved and immediately straightened again, and this change of form involves a continued pivoting of link within link, the friction being called into action by the tension which presses the surfaces together. Each link thus in succession resists this pivoting with a definite force, and the resistance, in effect, converts what appears to be a perfectly flexible combination into one possessing a tangible degree of stiffness, and the oblique attitude assumed by the chain as it approaches the bend, and the slight back turn which it assumes as it emerges from the bend, are alike consequences of this factitious stiffness.

For in virtue of gravity, the running chain, like the chain at rest, tends always to maintain the original catenary; and in virtue of its speed of rotation, it seeks to maintain (not preferentially the catenary, but) whatever form it for the moment possesses. Hence its departure from the true catenary was, as you saw, gradual. But when the figure of equilibrium is once attained, the persistency of form imparted by velocity serves to maintain this figure as indifferently as any other. Hence the figure is that in which equilibrium subsists between the force of gravity seeking to restore the catenary, and the factitious stiffness resisting the necessity of bending and unbending.

The slowness with which the form is assumed, and its steady persistency when once assumed, alike bear witness to the truth of the proposition which it is the object of the experiment to verify.

The stream of fluid in the tortuous flexible pipe would behave in a strictly analogous manner.

(To be continued.)

NOTES

It is with great regret that we hear of the death of Dr. von Willemoes-Suhm, the distinguished naturalist assisting Prof. Wyville Thomson in the *Challenger*. Information of the sad occurrence has just been received at the Admiralty.

At the opening meeting of the Royal Geographical Society on Monday, the president, Sir H. Rawlinson, reviewed the progress of the Society and of geographical discovery during the past year. He announced that the Prince of Wales, the Vice-patron of the Society, had just sent the Society, as the first geographical result of his tour in the East, a very interesting collection of route-maps of Upper Egypt and its recently acquired dependencies, which had been executed in the Topographical Department of the Egyptian War Office by General Stone, Chief of the Etat Major, from materials furnished in one direction by Col. Gordon and the officers serving under his orders, and in another by Col. Purdy and the officers of the Darfur Expedition. These maps contain much new geographical matter. The President referred with great satisfaction to Stanley's exploration of the Nyanza, and exhibited a complete chart of the lake drawn by Stanley. As to Col. Gordon, who by last accounts had reached Appudo, 140 miles from the Albert Nyanza, if he could overcome the eight miles of rapids which lay before him, he would probably reach the Albert Nyanza with his steamer the *Khedive*, before Stanley. Both Gordon and his assistant Chipendall report, from native information, that the Nile leaves the Albert Nyanza by two channels. Dr. Pogge and Dr. Lasaulx, the only remaining members of the German African